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The need for accurate prediction of the coastal ocean environment conceivably extends to the entire world's coastline. Since not all regions are of sufficient economic and sociological importance to justify operational modeling on a continuous basis, it is necessary to have available an alternative approach for short term on-demand forecasting. Such prediction may be in response to a man-made catastrophe or natural disaster. It may also be useful for coastal management in both developing and developed countries.

Developing a coastal ocean forecast system is a complex effort that entails data processing as well as numerical modeling. In order to evaluate the coastal hydrodynamic model, which is the kernel of the forecast system, it is necessary to acquire a wide range of oceanographic data in different environments. Comparing model predictions to such field observations will permit the determination of the usefulness of the model for real-time applications. This paper summarizes some of the data processing methods being incorporated into a prototype relocatable forecast system. As an example of the utility of the model, it is compared to observations of temperature from the inner continental shelf of southern California.

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Developing a Relocatable Coastal Ocean Forecast Model

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Introduction

The need for accurate prediction of the coastal ocean environment conceivably extends to the entire world's coastline. Since not all regions are of sufficient economic and sociological importance to justify operational modeling on a continuous basis, it is necessary to have available an alternative approach for short term on-demand forecasting. Such prediction may be in response to a man-made catastrophe or natural disaster. It may also be useful for coastal management in both developing and developed countries.

Developing a coastal ocean forecast system is a complex effort that entails data processing as well as numerical modeling. In order to evaluate the coastal hydrodynamic model, which is the kernel of the forecast system, it is necessary to acquire a wide range of oceanographic data in different environments. Comparing model predictions to such field observations will permit the determination of the usefulness of the model for real-time applications. This paper summarizes some of the data processing methods being incorporated into a prototype relocatable forecast system. As an example of the utility of the model, it is compared to observations of temperature from the inner continental shelf of southern California.

Background

A coastal ocean forecast model requires accurate prescription of environmental variables such as coastline position, water depth, wind stress, water surface height and transports at open ocean boundaries, inflow from rivers, heat and buoyancy fluxes, bottom type, and the initial distribution of temperature and salinity. Developing this type of model for a given region is made easier by a substantial observation program. An extensive measurement effort is not possible for a relocatable model, however. These models may be required to be deployed within time spans of a few hours, and return results within 12 hours or less. Because of these constraints, a relocatable model should be fully deterministic and make extensive use of remotely sensed ocean variables and operational forecast products. The model system being developed in this work is designed to give 48-hour forecasts that can be updated every 12 hours.

The basic premise to the present approach is that coastal ocean circulation should be simulated in the most realistic manner possible. This means using a baroclinic, three-dimensional (3D) primitive equation numerical model. This kind of model can be applied equally to tide- or wind-dominated coastal seas. It can also be used for any stratification conditions. The short time interval for the simulations relaxes some of the numerical constraints commonly applicable to LAM's (Limited Area Models; e.g., Shulman and Lewis, 1996).

Previous work (e.g., Keen and Glenn, 1998) has shown that numerical hydrodynamic models have improved accuracy when more environmental information is included in their initial state and boundary conditions. Thus, we endeavor to incorporate remote sensing as well as in-situ data where possible. Sometimes it is necessary to estimate environmental conditions, especially temperature and salinity. When this is done, a method is used that relies on known stratification within the area of interest. For example, temperatures for many coastal areas can be initialized using available temperature profiles and satellite altimetry (see Carnes et al., 1990). The temperature profile in very shallow coastal areas can be approximated using a simple relationship:

$$T(z) = \frac{T_s - T_B}{1 + 1.76 \cdot \exp(z - 4)} + T_B \qquad 1$$

This method permits the use of SST (Sea Surface Temperature) estimated from AVHRR (Advanced Very High Resolution Radiometer) 1 km data. The initial SST is then used to generate a 3D temperature distribution from equation 1. Unfortunately, no similar procedure is available for salinity, and it must be estimated from available data or measured prior to model operation.

In order to determine the overall model accuracy for predicting 3D fields such as temperature or currents, it is necessary to use a metric that can measure both vertical and horizontal error. The average Root Mean Square Error (RMSE) can be computed for a given depth z as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2} \qquad 2$$

Forecasting Methods

Hydrodynamic computations are completed with the Princeton Ocean Model (POM; see Oey et al., 1985). As implemented for RLAM (Relocatable Local Area Model) applications, POM can incorporate wave breaking as a source of turbulence near the surface and a combined wave-current bottom shear stress. The model grid is interpolated from available bathymetry databases which are then hand-edited to match the most accurate coastline available using an ARC/INFO-based GUI (Graphical User Interface). The model is intended for use with a horizontal resolution of approximately 1 km. A higher resolution is not used because of the limitation of the available AVHRR-derived SST fields.

Boundary conditions

Open boundary conditions consist of water surface heights and depth-average transports. Baroclinic (depth-dependent) currents, temperature and salinity are relaxed to prescribed values with a radiation condition to permit waves generated within the model domain to escape. For

stand-alone operation, only tidal elevations and transports are supplied. When nesting to coarser models is possible, the coarse model can supply the depth-dependent forcing as well.

Since a forecast model cannot be forced by observed winds, the wind stresses must be available from a forecast wind model. Currently, wind forcing is from either the Navy Operational Global Atmospheric Prediction System (NOGAPS) or Coupled Ocean-Atmosphere Prediction System (COAMPS) forecast models. The hydrodynamic model is typically spun up using only tides for 48 hours, and then run in prognostic mode for the forecast interval of 48 hours using predicted winds.

Initial 3D temperature and salinity fields

It is important to initialize a numerical model with accurate temperature and salinity fields, especially if one purpose of operating the model is to predict these variables' evolution over the forecast interval. There are several methods of creating such fields, depending on available data.

CLIMATOLOGY

The Modular Ocean Data Assimilation System (MODAS) at the Naval Research Laboratory maintains a global bimonthly temperature and salinity database with a resolution of 0.5° in both latitude and longitude. Individual temperature profiles are computed by a local regression at each depth based upon seasonal climatological data. Salinity is computed as a function of temperature. These profiles are available for deeper water off of the shelf and are considered a first-estimate of the coastal distributions only.

PROFILE EXTRAPOLATION (3D/CTD METHOD)

Generating a 3D field from a limited number of profiles requires both interpolation and extrapolation techniques. The approach we use first interpolates horizontally using inverse-distance weighted averaging (IDW) to fill in the space between observation points. A radial extrapolation technique is then used to extend the data to the rest of the grid. This technique divides the grid into eight equal quadrants corresponding to 45° of arc. The extrapolation within each quadrant is actually a linear interpolation between the data value farthest from the center and a boundary value that may be taken from climatology or other observations. This radial field is smoothed. IDW is then used to convert this grid to the model grid. When the vertical extent of profile data is limited, a climatological profile is used to fill in the remaining levels down to the maximum depth of the model grid. Each grid point is then smoothed vertically with a three-point filter. The resultant initial condition preserves the original structure of the profile data.

AVHRR EXTRAPOLATION (AVHRR/CTD METHOD)

Mean temperature and salinity profiles are calculated from the profile-based fields (above) by averaging over all grid points. The resultant mean temperature profile is adjusted over the upper 3 m to the AVHRR-estimated SST. When the AVHRR image is cooler than the profile, the transition part of the profile is smoothed. The remaining portion of the vertical profile remains unchanged. The mean salinity profile is unchanged.

The much simpler thermal structure of very shallow water near the coast can be simulated using equation 1. This is convenient since up-to-date observations are usually lacking. Using equation 1 and a climatological value for the bottom temperature, profiles can be computed using SST for coastal areas.

Using this method depends on the availability of good AVHRR data with a 1-km pixel size. Two problems occur in estimating SST from these data. First, most images are incomplete and we have found it difficult to get a good one when we need it. A simple compositing method has been developed that allows a user to view the available images and choose those to be used. These are then merged using two criteria: (1) more recent images are higher priority; and (2) the image with the warmest value of SST for a given pixel (warmest pixel method). The user then has the option to smooth the resulting image as desired. Although such composites are not ideal, they can give good values in critical areas while allowing the numerical model to be run with reasonable values in areas of limited interest. The second problem we have found with the 1-km AVHRR data is that bad points can easily slip past correction algorithms, especially near land. These can be corrected by the user with the same ARC/INFO GUI that is used to edit the model grid. The advantage of this system is that is very efficient for a moderately knowledgeable user.

Application to Southern California

The coastal forecast system is currently being evaluated in several areas, including southern California (Figure 1). As part of a field study in this area, coastal surface currents, and a large database of both ADCP (Acoustic Doppler Current Profiler) and CTD (Conductivity, Temperature, Depth) profiles were collected between October 17 and 26, 1995. This database is being used to examine the model's predictive skill for currents, temperature, and salinity with respect to the model's initial condition and the wind stress. The model skill for predicting the 3D temperature field and surface currents is compared to persistence at 24 hours, using the depth-dependent RMSE (Equation 2).

The southern California model uses a Cartesian grid with a resolution of 1 km. The grid is rotated counter clockwise 40°. Bathymetry was derived from 7' (approximately 181 m) National Ocean Service (NOS) data, with a minimum depth in POM of 3 m. The circulation model is spun up for 48 hrs, and the hindcast begins at 0000 GMT 17 October.

Four initial temperature fields were used in this study: (1) a single MODAS profile; (2) a 3D field produced from the CTD profiles collected on 17 October; (3) a mean profile of all data from 17 October; (4) a 3D field found using the mean profile and the AVHRR-estimated SST at 2100 GMT, 16 October. The maximum vertical extent of the CTD data is 163 m, so the MODAS profile was used to fill in the remaining levels down to the maximum depth of the model grid (1250 m).

A number of atmospheric forecast systems have been examined and found to vary significantly in their predicted winds in different environments (Rienecker et al., 1996). The accuracy of the wind has also been found to influence predicted temperature and currents in numerical models (Chu et al., 1999). Since most of the atmospheric models operate at large scales compared to the RLAM, they may not adequately include coastal topographic effects and may thus fail to predict nearshore winds accurately. For this reason, a comparison is made between simulations with NOGAPS winds (Figure 2) and winds measured at the boat marina at

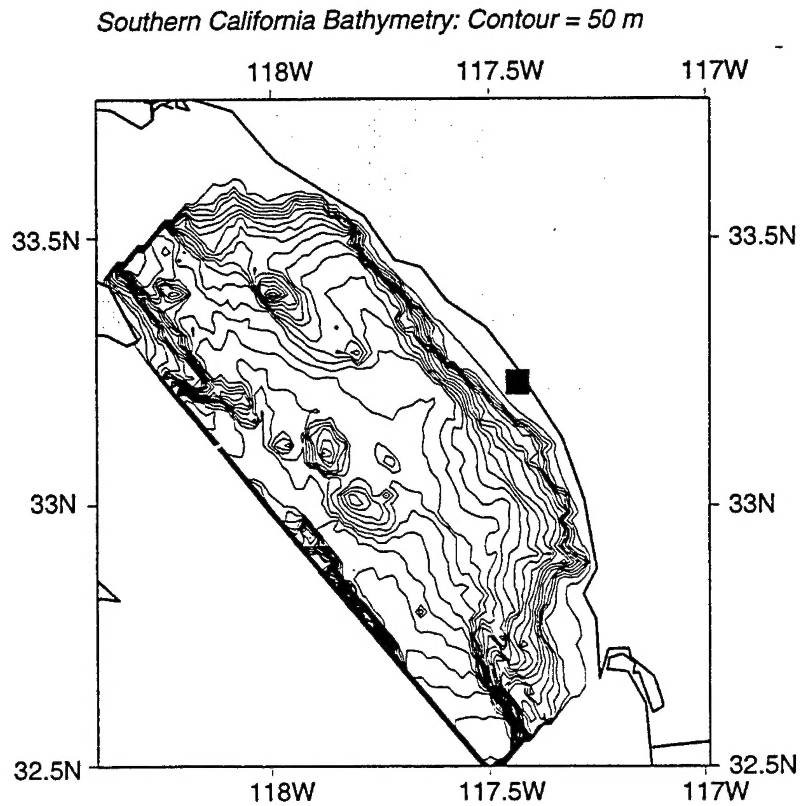


Figure 1. Bathymetry map of the model grid. The location where hydrographic surveys were conducted is indicated by a black square.

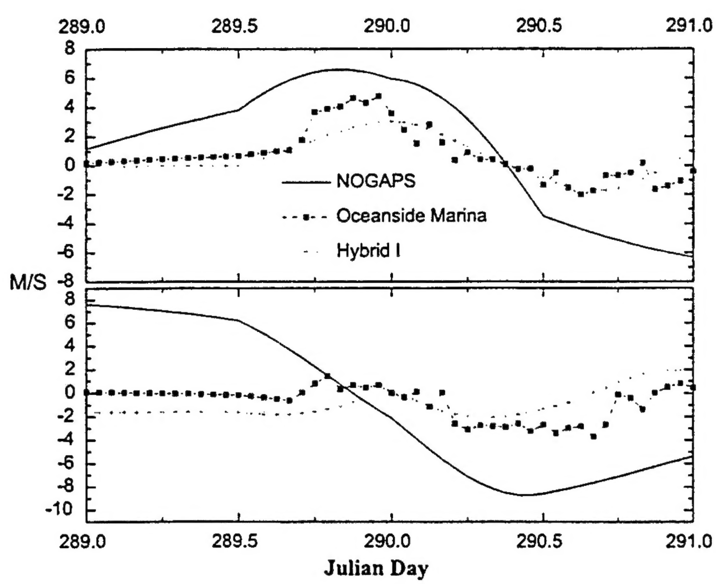


Figure 2. Time series of zonal (upper) and meridional (lower) wind components from wind fields used in model. Julian Day 289 corresponds to 16 October 1995.

Oceanside, California. In addition, hybrid winds were used that merged the two primary wind sources.

Model Skill Analysis

Field measurements

Hydrographic cruises completed on 17 and 18 October 1995 collected CTD data (Figure 3) on the narrow shelf west of Oceanside, California. The Sea-bird Model 19 Seacat CTD sampled at a rate of 2 Hz and binned over 1-m depth cells. The lowering rate was 30 m/min. Only downcast profiles were recorded. Each CTD grid consisted of between 21 and 26 stations. Hydrographic data collected on 17 October were used to create initial conditions. Data from 18 October were used in the skill evaluations.

Model results

A complete error analysis has been completed for temperature and salinity data from the hydrographic profiles, as well as the 3D currents from the ADCP surveys. The error results for temperature and salinity are similar, and only temperature is discussed below. The currents are beyond the scope of this paper.

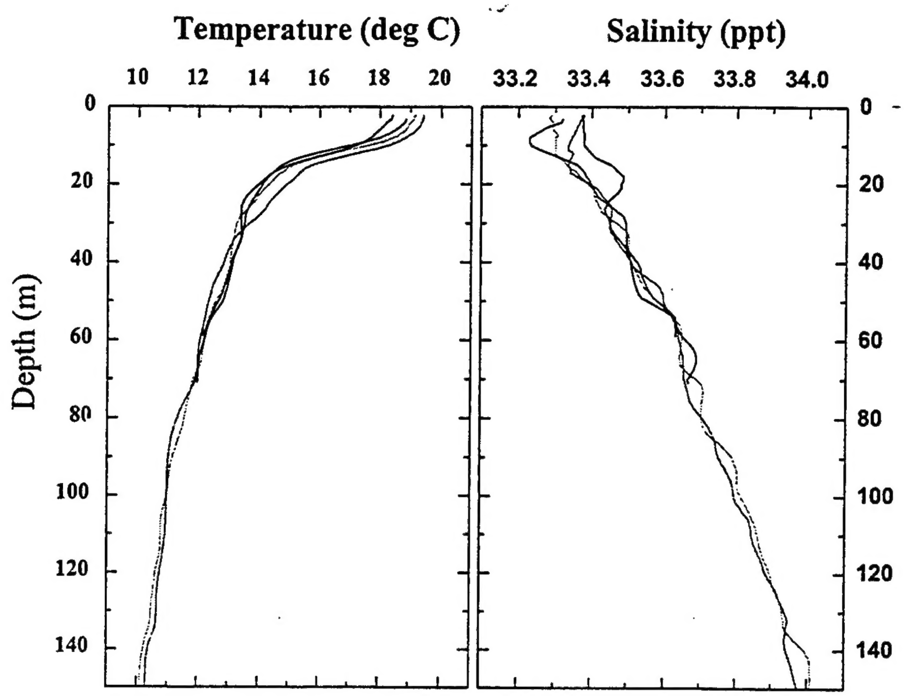
SENSITIVITY TO INITIAL TEMPERATURE FIELD

The AVHRR/CTD and mean CTD initial conditions for temperature vary at only the upper three meters, over which the AVHRR/CTD method replaces the mean value. However, many of the lower temperatures in the SST do not occur within the study area, so their influence on the initial temperature is unknown. The difference between the simulations using these two initial conditions is minimal and only the AVHRR/CTD results are discussed below.

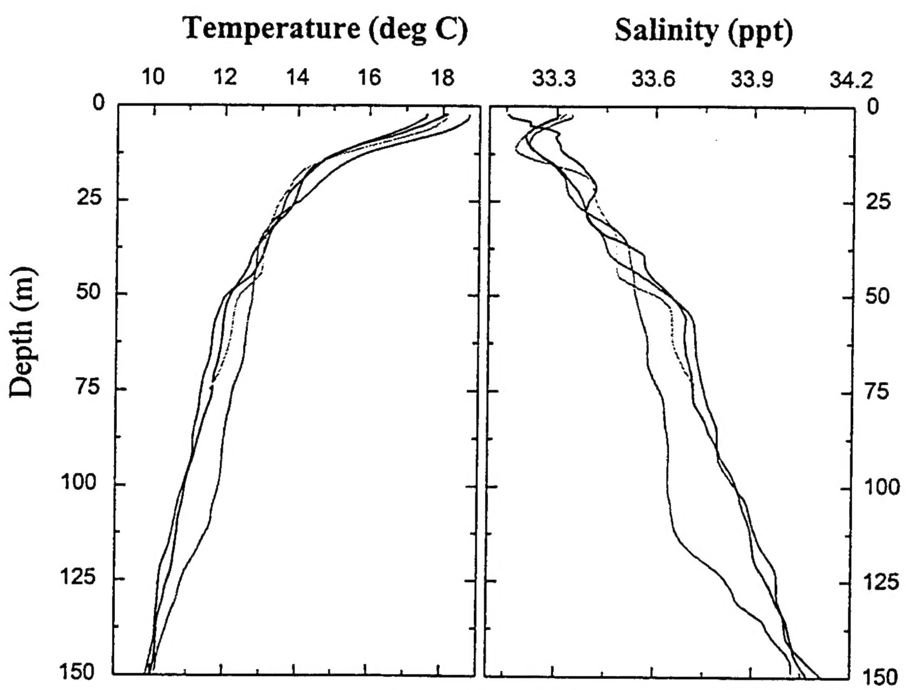
The MODAS climatology produced larger errors (Figure 4a) over most of the water column than the other initial conditions, for both the marina and hybrid wind forcing. The NOGAPS wind resulted in smaller errors for the MODAS climatology, but most of the errors for this initial condition were larger than for either the AVHRR/CTD (Figure 4b) or 3D/CTD (Figure 4c) initial conditions.

The AVHRR/CTD profile (Figure 4b) resulted in a fairly uniform error distribution with depth for both the marina and hybrid winds. The RMS error is less than 1°C at the surface but increases rapidly for the hybrid wind. The error does not exceed 1°C until a depth of 40 m for the marina winds. However, only the marina wind is better than persistence (solid line), and only above 20 m. Persistence is calculated using the temperature profiles from 17 October in equation 2 in place of the model output.

The 3D/CTD initial condition leads to an improvement (Figure 4c) over persistence throughout the water column. This performance is associated with both wind fields that included the marina winds. This indicates the relative slowness with which temperature changed below the mixed layer. It also indicates the error in mixing caused by the excessive surface stress of the NOGAPS prediction.

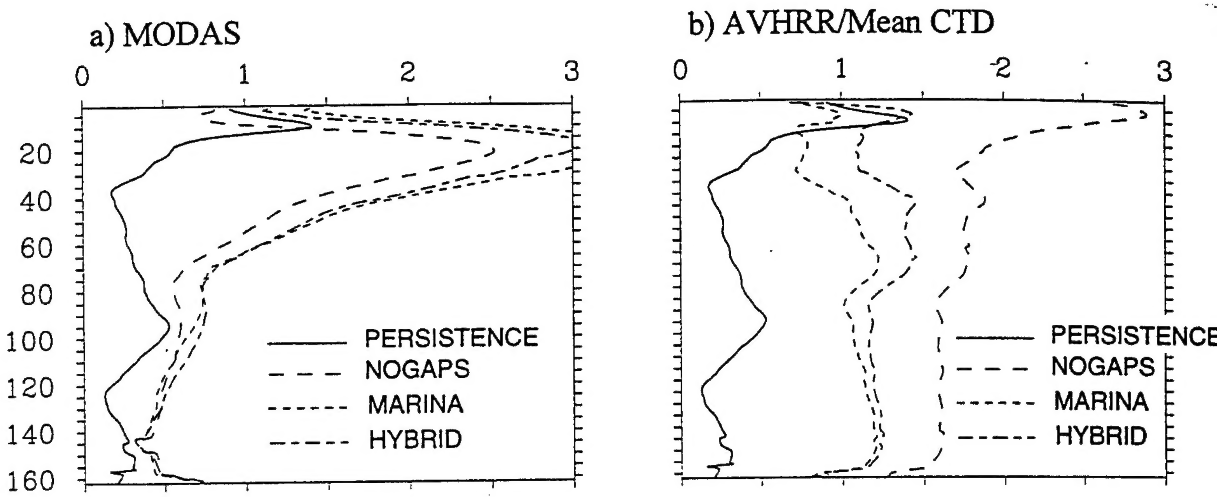


17 October 1995



18 October 1995

Figure 3. Plots of typical CTD data from the California study area. The shorter segments are from stations in shallow water. The location where hydrographic surveys were conducted is indicated by a black square in Figure 1.



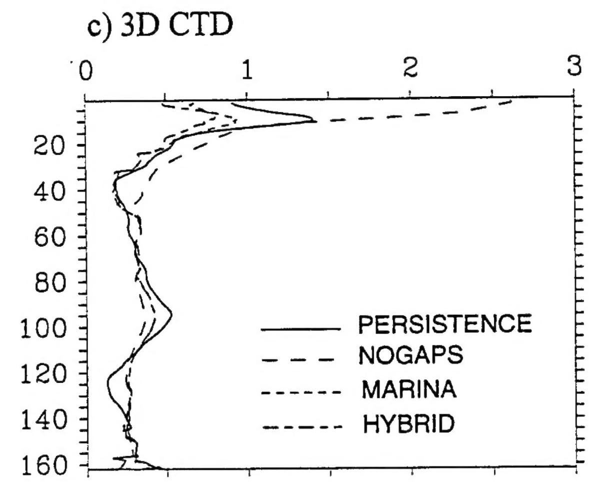


Figure 4. Plots of RMS error (Equation 2). The value at each depth is the average of all data-model pairs at that depth. Persistence uses the data from 17 October.

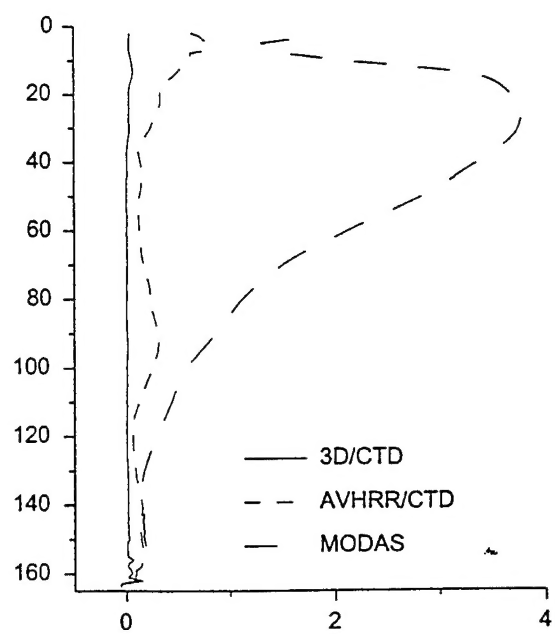


Figure 5. Plots of RMS error (Equation 2) for initial conditions. The value at each depth is the average of all data-model pairs at that depth.

SENSITIVITY TO WIND

The marina winds are influenced by local topography. The NOGAPS wind field is from a global operational forecast product with a resolution of 1 degree of longitude and latitude. The hybrid wind is a linear combination of the others, in an effort to balance nearshore and offshore forcing. The magnitudes of the *u* and *v* components of the NOGAPS winds (Figure 2) are significantly higher than the either the marina or hybrid winds. Note that the time series from Figure 2 are taken near the coast.

When the MODAS climatology is used for the initial temperature distribution (Figure 4a), the model's response is very similar for all of the wind fields. As real observations are incorporated, however, the NOGAPS wind produces a larger error throughout the water column (Figure 4b), with surface errors as much as 2°C higher than for the other wind fields. Interestingly, the RMS error for the NOGAPS wind is greater for the AVHRR/CTD temperature distribution than for the 3D/CTD case, relative to the other winds.

Discussion

An important consideration in evaluating the results of this study is the error in the different initial temperature conditions (Figure 5). The initial error is practically nil for the 3D/CTD distribution. The MODAS profile exhibits the greatest error, as is expected with climatological data. The slight difference between the 3D/CTD and AVHRR/CTD profiles indicates the amount of spatial variability within the study area.

The RMS error for the MODAS climatology is higher than most of the other simulations, suggesting that climatology should not be used if any CTD data is available. The lower error of the NOGAPS simulation, relative to the other wind fields used with the MODAS initial condition, can be seen as an example of the conclusion of Keen and Glenn (1998); the best possible initial condition improves forecast skill only when more realistic model physics are incorporated. In this study, realistic physics are introduced through the wind stress computed from the coastal winds. It is significant that the RMS error associated with all MODAS simulations decreased below 20 m, after the model had run for 24 hours. In other words, all of the wind fields improved the climatological temperature profile using timely environmental forcing and realistic model physics.

The hydrodynamic model is sensitive to the initial condition. The error difference between the AVHRR/CTD simulations and the 3D/CTD simulations is greater than the initial error, for all wind fields, below 20 m. The 0.5°C difference in initial error between the 3D/CTD and AVHRR/CTD temperature at the sea surface is a result of skin processes that were not captured by either the method of generating the initial conditions, or the model physics. The general increase in surface error, however, is a result of too much mixing in the model. As a result of wind-induced mixing, the surface error is greatest in the 3D initial conditions with the NOGAPS wind fields. It, therefore, appears that the nearshore temperature structure is controlled primarily through local effects.

Conclusions

Developing an operational relocatable coastal ocean forecast system entails both data processing and numerical modeling efforts. It is important to make maximum use of both remote sensing and in-situ data to force a coastal hydrodynamic model. It is also necessary for the resulting system to be operated within a short time interval, and produce accurate forecasts of ocean variables, such as currents, temperature, salinity, and elevation, for intervals up to 48 hours ahead.

Two important factors in the accuracy of a numerical hydrodynamic model are the initial temperature and salinity distribution, and the wind stress. The initial temperature field can be taken from a large set of observations or, in a more likely scenario, from SST derived from AVHRR, used in combination with a limited amount of hydrographic data. The wind stress can only be predicted from an operational forecast model, such as NOGAPS. It may be necessary, however, to implement a coastal wind model for some regions.

This study uses the vertical distribution of RMS error to analyze the skill of a baroclinic, 3D, primitive equation model (the Princeton Ocean Model), which is part of a coastal forecast system being developed. We have found that the model is sensitive to the initial condition, and that initial error does not simply propagate through the model. This study has shown that if the local environment is poorly known, it is not as important to include the most accurate physics in the numerical model. If, however, recent observations are available, it is necessary to increase the physics within the model system in order to improve the forecast accuracy. The error for temperature suggests that local processes dominate in a coastal oceanographic environment, and these must be included in a forecast model system.

Nomenclature

M = model-predicted value of prognostic variable
O = observed value of variable
N = number of stations with values at each comparison depth
T_S = surface temperature
T_B = bottom temperature
z = depth below surface

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